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ADVANCED MECHANISMS FOR ROBOTICS

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INTRODUCTION

In recent years NASA has launched an extensive effort in robotics for space applications; the idea being to assist and augment manned space flight and, perhaps equally important, to give a major boost to U.S. industrial competitiveness by transferring the technology into the private sector. In this effort, research on mechanisms, actuators and motors and their associated sensors and controls, has traditionally been sacrificed on the altar of a rush for more and more "compute power", sophisticated graphical and animation packages and controls techniques. This, of course, results in lopsided progress; twenty first century computers and controls coexisting side-by-side with nineteenth century mechanisms, actuators and motors. But; robotics is a systems challenge and if one portion of the system is limited, the system is limited. A balanced approach to R&D is a must if real systems progress is to be made. The intent of this paper is to show what is being done at GSFC to bring about this balance and, as a by-product, the benefits and opportunities open to U.S. industry.

Accordingly, an overview of applied research and development at the Goddard Space Flight Center (GSFC) on mechanisms and the collision avoidance skin for robots is presented. First the work on robot end effectors is outlined, followed by a brief discussion on robot-friendly payload latching mechanisms and compliant joints. This, in turn, is followed by the collision avoidance/management skin and the GSFC research on magnetostrictive direct drive motors. Finally, a new project, the artificial muscle, is introduced. Each of the devices is described sufficiently to permit a basic understanding of its purpose, capabilities and operating fundamentals. In addition, the development status of each is reported along with descriptions of breadboards and prototypes and their test results. In each case, the implications for commercialisation is discussed. The chronology of the presentation will give a clear idea of both the evolution of the R&D in recent years and its likely direction in the future.

I. END EFFECTORS

In this section, GSFC end effector R&D is discussed. The GSFC "Gripper-Nut Runner" (fig. 1) is described first, followed by a new emerging concept based on "Spline Screws".

The "Gripper-Nut Runner" has been under development at GSFC for more than three years and has evolved to the point shown in Fig.1. Since space is a "micro-g" environment, objects must be fastened to something (say, for example, Space Station) to prevent their drifting away. The function of the "Gripper-Nut Runner", therefore, is to grasp a dedicated interface attached to such an object using the gripper and to use the nut runner to loosen the fastener which fixes it to Space Station. This permits the robot to grasp objects and unfasten them and to move and re-attach them. This system has been proven in the GSFC robotics lab as well as several other NASA-affiliated activities around the country. It is rugged and durable and has repeatedly withstood forces at the finger tips on the order of 200 lbf. Of its component subsystems, three have commercial possibilities.

a. The "Split-Rail" Parallel Gripper [1]. This device(the gripper portion of the system shown in Fig. 1), was designed and patented by a NASA engineer, and has obvious commercial possibilities as a general purpose industrial gripper. This is a high performance wide throw parallel action gripper that uses a unique "split-rail" concept to make it simple, light, and compact (hence, inexpensive to manufacture). It is made primarily of anodized aluminium with straight machining cuts (no grinding) and rolls on cylindrical bearings throughout its stroke and so is strong, precise, responsive and will not jam under side loads.

b. Very Large Scale Integration (VLSI) gripper controller [2]. This state-of-the art gripper controller was developed as part of a NASA Small Business Innovative Research contract (SBIR). It is a dual-axis system that incorporates unique and innovative custom Application Specific Integrated Circuits (ASPICS) to permit unusual performance in terms of filtering, precision and smoothness of motor control. It has a unique and compact power supply system to permit its being mounted on the gripper. Interfaces, hardware and software are kept serial and simple. This system is fully developed and functional. It has obvious commercial implications for any type of servo joint. For example, it can readily be adapted, in a modular fashion, to form the basis for an entire robot control system.

c. Rolling Friction Fingers [3]. These simple and compact gripper fingers (Fig. 1) provide a vectored, rolling friction guidance and locking system between the robot gripper and the dedicated interface. Invented and designed in-house at GSFC, these fingers enable the gripper to acquire a dedicated interface of an object despite large initial misalignments and to guide the gripper to a seat and lock with the object, providing low friction and smooth operation throughout, despite the presence of large side forces. It permits the gripper to release the object under strong side loads, a very important safety hedge against the object being caught and jammed in the jaws. Also, because of its rolling action, it cannot scar or "burr" the object regardless of the forces. And, because of this rolling action, force feedback sensing is cleaner and the size of the motors required to drive the gripper screw can be reduced. Most of the GSFC grippers are equipped with this device. It has proven out in the laboratory over continued use; in one instance, for example, permitting a weak gripper motor to release an object under side loads of 100 lbf. and consistently making it easier for robots to acquire and grasp objects using both passive and/or active compliance. This should have a wide range of commercial applications wherever guidance and latching and locking of objects is required under conditions of large misalignments and opposing forces.

d. Wrist-Driven Auto Changer [4]. Invented and developed in-house at GSFC, this simple, compact and strong device provides a safe and reliable means for space robots to exchange end effectors. It is actuated by a unique simple camming action which occurs between mechanisms in a tool interface plate, a keying element in the tool storage holster and another mechanism attached to the robot as the robot stores or removes the tool. The entire system is passive with all action being initiated by the robot actuators and controls. Hence, many of the sensors of the robot joints can be used (to include the encoders or resolvers and the wrist 6 vector force feedback sensor) to aid in monitoring the status of and controlling the Auto Changer. Also, many of the interfaces to robot control are already inherently taken care of. The device is inherently safe and reliable because one of the prime sources of Auto Change mishap, inadvertent release, is impossible. It has been tested extensively in the GSFC robot lab and has met or exceed every expectation. It has even been operated in a teleoperator mode without force feedback-a very difficult feat. This should have a limited; but significant niche' market in the commercial world.

GSFC is in the process of developing an entirely new approach to end effectors based on a simple straight-forward concept called "Spline Screws" [5]. This concept was invented and developed in-house at GSFC and represents an entire space fastening strategy of which end effectors is but one portion. We will develop the explanation of this concept by a simple example (fig. 3). We assume that the robot wrist has a dual roll capability about a common center. The inner roll terminates in a splined screw driver and the outer roll provides the means to rotate the object being grasped. This constitutes our end effector. The object to be moved is pierced by a screw (typically 0.5 in. dia.) which is splined so as to mate with the splined screw driver on the one side and the fixture to which the object will be attached on the other. The place of attachment has a small rotating fixture which is splined to cooperate with the piercing screw of the object on the side away from the gripper. We will begin by assuming the object is fastened to an attachment point. The robot would position the end effector over the splines of the screw piercing the object. The robot would guide and seat the inner roll splined screw driver and then guide and seat the outer roll torque tabs into slots in the top of the object. The splined screw driver would be turned clockwise. The splines of the screw driver would mesh and lock with those of the object screw, the object screw would turn with the rotating fixture. In the process, the object screw would translate towards the attachment fixture. This would unlock it from the fixture and lock the object to the end effector. The end effector would be free to leave with the object and maneuver it pending attachment to another fixture. Once aligned with and seated on this new fixture, the end effector would be turned counter clockwise and the object screwed off the end effector and onto the new fixture. The object would be either attached to the end effector or the attachment fixture or both at all times.

The splines permit the end effector screw driver to capture the object screw yet are sufficiently course that cross-threading between the two would be impossible. The same would be true of the interface between the object screw and the attachment fixture. On the other hand, the object screw would be captive in the object so it could have a very fine thread with a short lead and be lubricated to give great holding forces with modest amounts of torque (approx. 600 lbf from 8 ft-lbf torque typical). The system would not backdrive so brakes would not be necessary on the screw driver and an attached object could survive launch forces. It is also clear that foot prints on the object and the attachment fixture would be very small (on the order of 1.25 in dia.) as would the end effectors. The system would be basic, simple, strong and very reliable. It would also be extremely versatile.

To demonstrate the versatility of the "Spline Screw" technique the example of an Auto Change is given. In this case we attach the screw to a common tool interface by means of slightly compliant wavy springs. But where the nut was the pierced object in Fig. 2, it is an electrical connector in the Auto Change which is partially trapped so that it can move in translation only with respect to the common tool interface. Thus, as the screw is turned, the electrical connector nut would translate upwards, inserting the pins into the end effector electrical connector and releasing the Auto Change and its tool from its holster. At this point, the connector nut would be stopped by the upper portion of the Auto Change. But; the screw would still be turning so it, in turn, would translate downwards towards the tool, compressing the lower wavy spring washer in the process. In doing so, however, The Auto Change and end effector would seat and lock together. The process of storing tools would be the reverse. The screw would be turned counterclockwise, the nut would translate down until the tool locked to the holster. In the process the tool and electrical pins would separate from the end effector. Torques required would be modest (approx. 8 ft-lbf.) and the system would seat and lock or store with authority and certainty. And, of course, the dimensions and weights would be minimal.

II. ROBOT-FRIENDLY PAYLOAD LATCHING MECHANISMS.

It appears the most efficient robot-friendly payload latching mechanism to date would simply use the "Spline Screw" approach in yet another configuration. The design is closely related to the Auto Change described above; with a few minor additions.

III. COMPLIANT JOINTS.

Compliance is a critical component in the interaction between the robot and the object being grasped. Without it, a robot cannot capture, seat and lock an object. This almost always involves using passive(typically springs) and active(robot movement through sensor information)compliance in a cooperative manner. A GSFC engineer has pioneered numerous inventions in the area of passive compliance using a novel "Compliant Cable" [6] approach. With this approach cables can be wound and arranged in light weight, strong, and compact structures to provide vectored compliance. That is, the spring constant can be tailored independently in each of the six vectorial directions. The compliant cables, themselves, are composed of several strands wound around each other so they have a spring effect(coupled with impressive tensile strength); but with sufficient friction between the strands that the spring oscillations are damped out. This simple concept has been used as the basis for many devices in government and in industry of which only a portion would come under the heading of robotics. For example, these cables have proven to be excellent shock absorbers and vibration isolators for use in space and are also used extensively in the GSFC Robotics Lab. Commercial devices, based on this principle are already in extensive use. This is an important niche' market.

IV. COLLISION AVOIDANCE/MANAGEMENT SKIN.

Safety is a prime concern for robots operating in space; particularly when they are operating near humans and/or space structure. Thus, NASA is developing a collision avoidance/management skin wrapped around the robot arms. This skin will consist of an array of sensors each of which is called a "Capaciflector" [7](or capacitive reflector). Invented and developed at GSFC, this technique enables a capacitive sensor to be mounted in the immediate vicinity of the grounded robot arm and still "see" out to ranges an order of magnitude further than previously reported. For example, we routinely demonstrate picking up a human hand or a four in. dia. aluminium cylinder at ranges in excess of one foot using a 0.25 in. wide, four in. long strip of copper tape as a capacitive sensing element with an operating frequency of 20 khz and a potential of 10 volts. The previous state-of-the-art range of such a sensor is approximately one inch. Normally the electric field of a capacitive sensor couples both back into the ground plane and out towards an approaching object. The less the stand-off from the ground plane, the more the coupling into that ground plane and the less the coupling towards the approaching object. In the "Capaciflector" a shield is interjected between the ground plane and the sensor. This shield is driven at the same frequency and is in phase with the sensor. It is also at the same potential. However, it is electrically isolated from the tuning portion of the oscillator. Thus the sensor couples with an approaching object and changes the frequency of the oscillator (detection by standard fm techniques), whereas, the shield follows that oscillator frequency; but any coupling it may do to ground or the object does not effect operating frequency. The result is that for the sensor to couple to ground, its electric field must go around the shield to reach ground. Thus we have the effects of a very large stand-off. The sensors and shield,however, may be part of a very thin flexible printed circuit board mounted directly on the ground plane. The commercial prospects for such a sensor are, of course, very significant. It will, no doubt, one day be a standard feature of many of the millions of industrial capacitive sensors at work throughout industry.

V. MAGNETOSTRICTIVE DIRECT DRIVE MOTORS.

Current robot motors are very high speed; but have weak torque compensated by using a transmission with extensive gearing. Since safety brakes are also required in these joints, these brakes must be located to act on the motor itself or the drive shaft on the motor side of the transmission to give them sufficient holding leverage. All these additions, compensations and restrictions lead to complications, lower reliability and controls problems. The magnetostrictive motor project addresses these concerns by developing a device that has outstanding torque density and is self-braking with the power off. This permits the power to be taken directly off the drive shaft, eliminating brakes and transmissions. The magnetostrictive phenomenon using the material Terfenol-D shows promise because it generates impressive forces (> 4 ksi) and has excellent frequency response (6 khz for 0.25 in. dia. rod). However, it also has two significant drawbacks, it has a very short stroke (0.001 in./in.) and low magnetic permeability (5) [8]. These present formidable engineering challenges.

Two engineering approaches are pursued (Fig. 3); type A using the classical "inch worm" approach and type B using an original (more promising) approach based on a roller locking technique. A proof-of-principle type A device has been successfully tested. It produced 9 ft-lbf stall torque (a record for an electric motor of this size), had a 800 microradian step size (outstanding for precision control), consumed 600 watts power and had a no-load speed of 0.5 rpm. Sound generated by the pounding of the clamping rods was surprisingly modest. The device was 10.25x4.50x4.25 in. and weighed 39 lbs [9]. The weight is not significant, nor is the low speed since no effort was made to control weight and limit the inertias of the moving parts at this stage of development. Also, small diameter rods were used so even this breadboard is fundamentally underpowered. Never-the-less it is clear that with development, this motor will become very competitive with torques on the order of 100 ft-lbf and no-load speeds near 20 rpm. We are now poised to begin work on prototype B, bringing it to the same level as A. It should exceed A in torque, speed and have outstanding efficiency.

From a commercialisation point of view, two more years of development will be required before these motors are ready. Ultimately, however, we are expecting a niche' motor which will significantly extend the state-of-the-art in applications requiring low speed, safe, high torque in a modest-sized package.

VI. ARTIFICIAL MUSCLE.

It is clear that mechanisms, and hence robotics systems, are limited because we do not have a linear motor/actuator which can perform the functions of the basic muscle. Such a motor must both perform at the level of the human muscle (strength, compactness, linear stroke, frequency response, and controllability) and be able to consume fuel and produce power independent of an umbilical or large battery for expended periods of time. We are not seeking to reproduce the human muscle; only its performance. This project is being initiated at a highly qualified university under NASA/GSFC direction. It is realistic and results and products are, we feel, a near certainty. However, they are approximately three years away. The eventual commercial implications of this work will, of course, be very significant.

SUMMARY AND CONCLUSIONS

Highlights of the NASA/GSFC program in advanced mechanisms and sensors have been presented. From this overview four things should be clear. 1. There is a tremendous amount of work to be done, from basic screws to futuristic muscles. There are crippling inadequacies in our present capabilities every where. 2. The existence of these inadequacies is distorting and hindering the progress of robotics in general. 3. NASA/GSFC is doing everything humanly possible to plug some of the more glaring holes as quickly as possible. 4. There are important commercialisation opportunities to be realized throughout.

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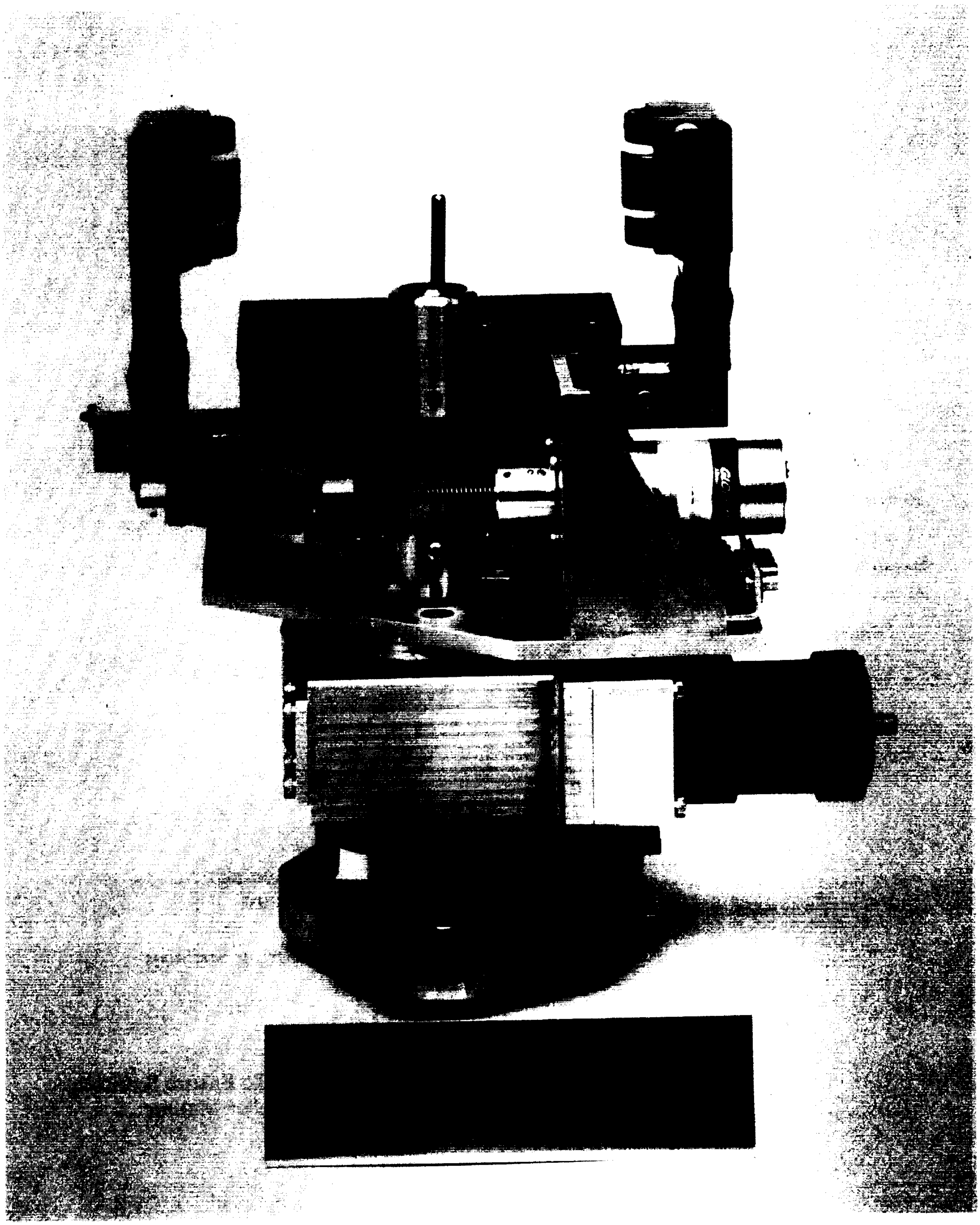


Fig. 1 THE GSFC "GRIPPER NUT RUNNER"

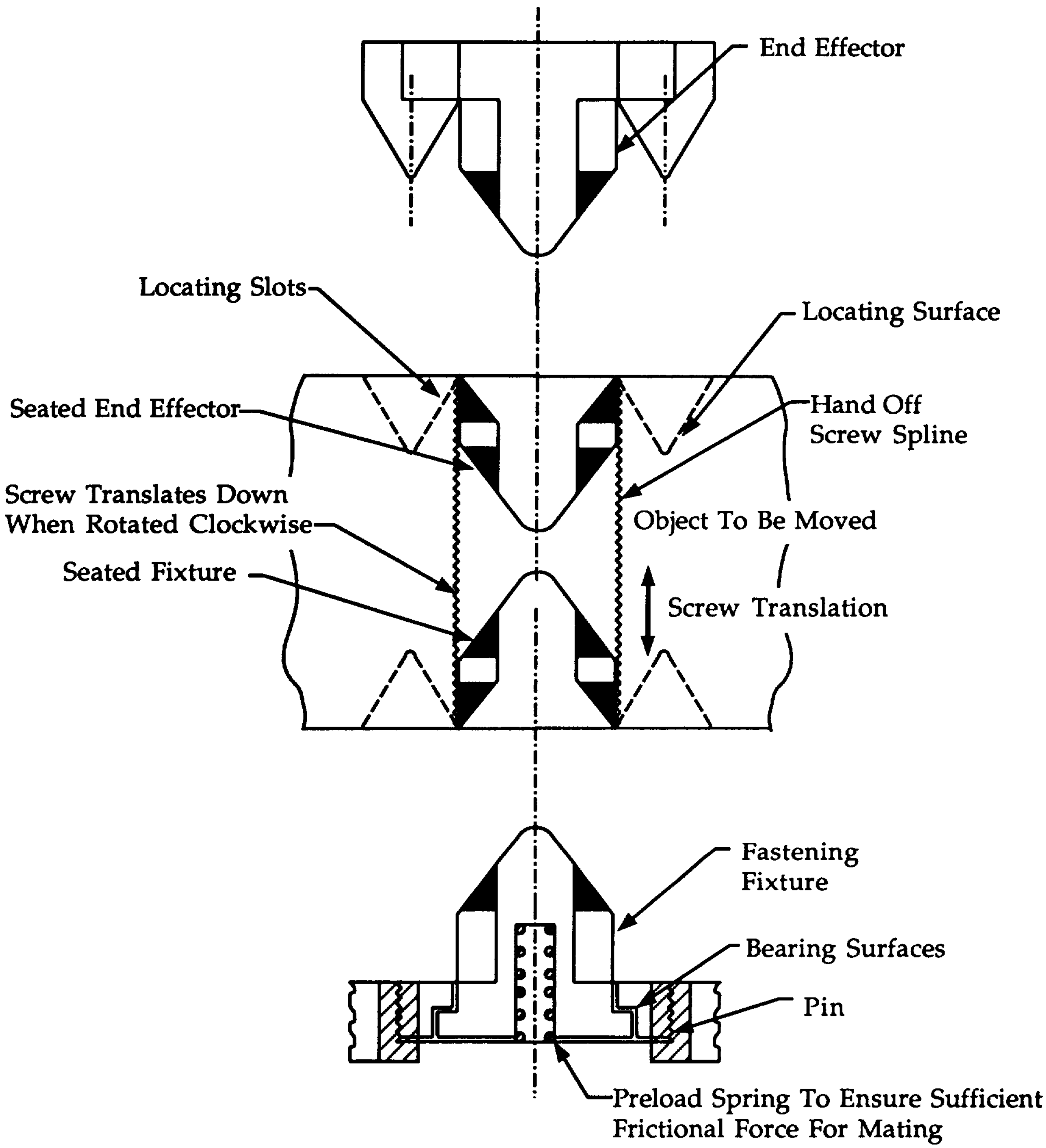
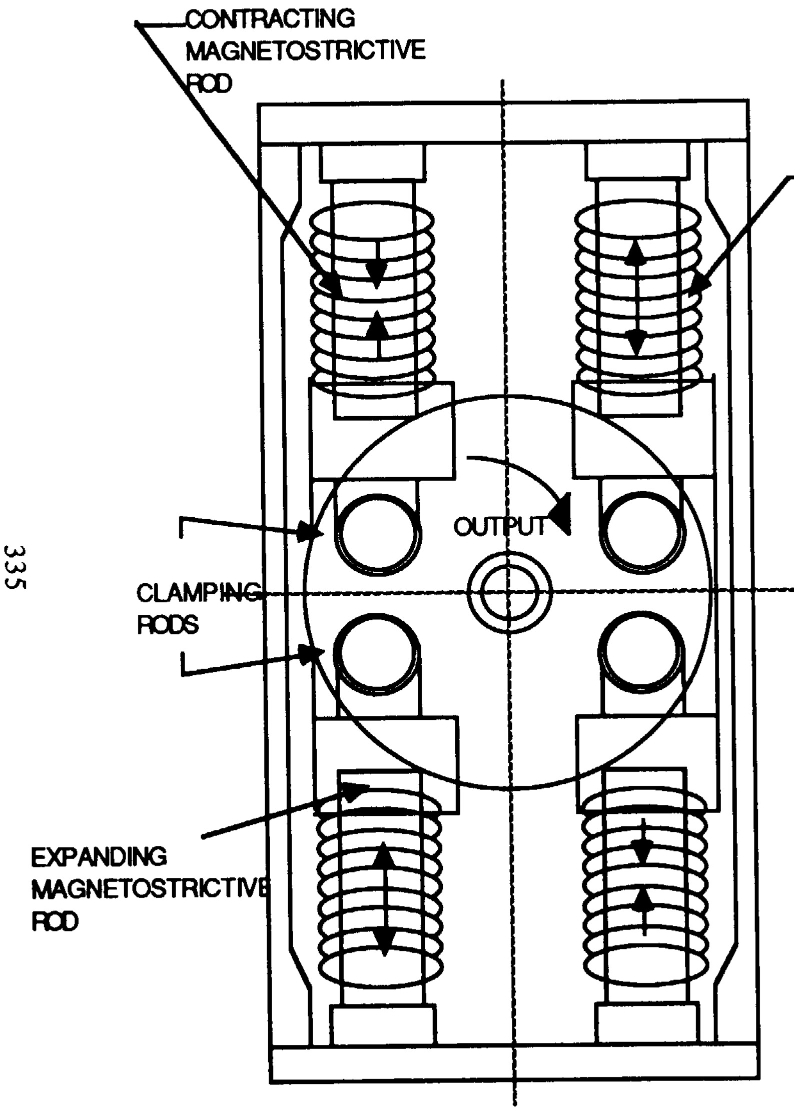


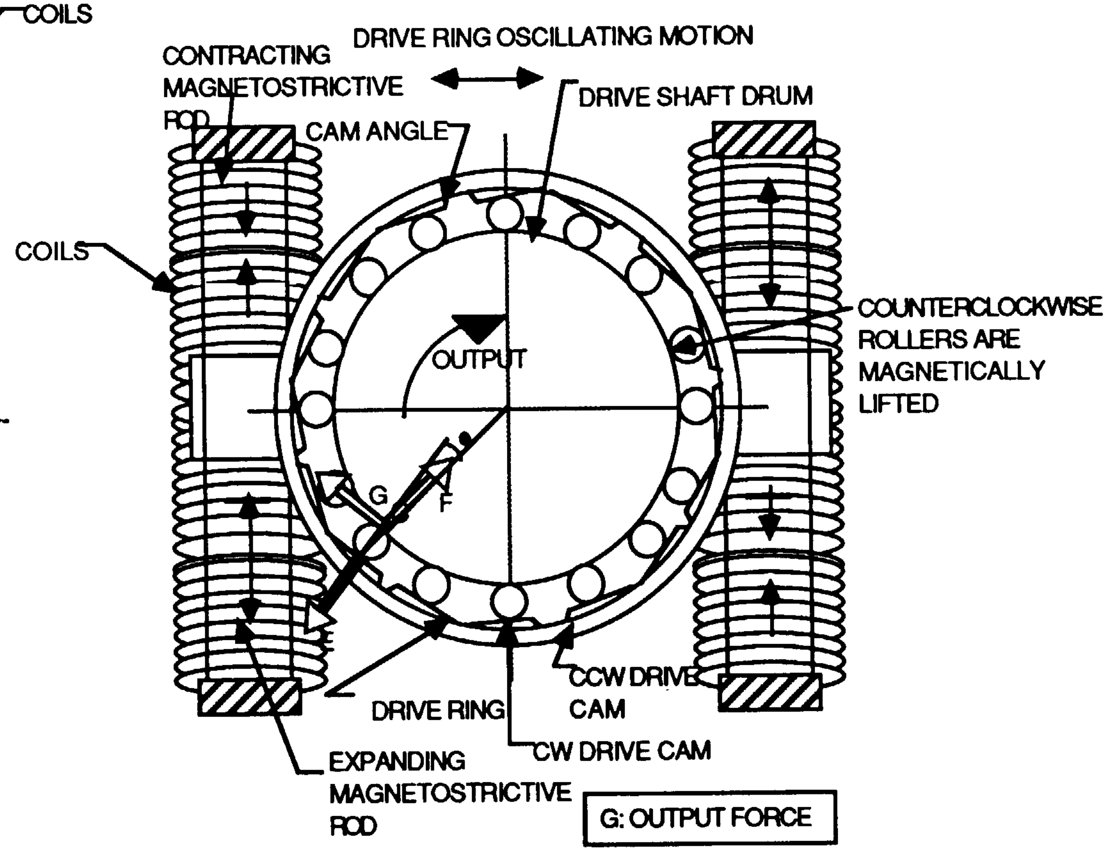
FIG. 2 FASTENING USING LOCKING SPLINES

FIG. 3 MAGNETOSTRICTIVE DIRECT DRIVE MOTOR

COMPETING DESIGN CONCEPTS



TYPE A: MAGNETOSTRICTIVE DRIVE
MAGNETOSTRICTIVE CLAMP



TYPE B: MAGNETOSTRICTIVE DRIVE
ROLLER LOCKING CLAMP